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Progress Report No. 5

System No. 2

Contract No. A-101

28 November 1955 to 22 January 1956

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Copy 2 of 7

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1-0. RESUME OF PROGRESS.

1-1. Circuit design of all major communication and navigation units is complete, and construction of an equipment for flight test is about 55% complete. All of the units being constructed for flight test are in final form, with the exception of the airborne navigation timing circuits, ground-based navigation circuits and ground-based communication timing circuits. These three units will have circuits identical to the production design, but will be constructed in the form of laboratory models.

1-2. Construction of the facilities to provide an operating site for the ground-based equipment during system tests is essentially complete. These facilities include a building to house the equipment and a class-C military rhombic antenna erected on a 15-acre site near Los Angeles. This antenna is oriented on a true bearing of 60°, permitting system tests on paths up to 2600 statute miles in length within the continental United States. A modified Collins 231-D transmitter and a portion of the System 2 equipment will be installed during the week of 23 January to permit preliminary testing of the navigation-system circuits.

1-3. A field test unit consisting of the airborne navigation timing circuits, a pulse transmitter, a 36-foot whip antenna, and a modified commercial communication receiver has been assembled to permit preliminary field testing of the navigation system timing circuits. Tests are planned to be made from the Denver, Colorado area during February, 1956.

1-4. A C-47 aircraft has been equipped with a long-wire antenna (similar to that of the operational aircraft) and with the necessary 400-cycle and 28-volt d-c power facilities for System 2 flight tests. Installation and test of the System 2 airborne equipment on this aircraft can commence after 23 January 1956. Flight testing of both the communication and navigation portions of the system is scheduled to commence in February.

1-5. Production design of the first System 2 assemblies was completed on 6 January. Production releases will continue until 15 February, the date scheduled for release of the last major unit. Design-engineering effort will be required for some time past this date to complete all drawings in good form.

1-6. A study of the problems of converting radio-path range to ground range, and of converting two or more ground ranges to geographical position, has been completed. Graphical procedures, described in paragraph 2-6, have been developed to accomplish these functions.

2-0. NAVIGATION PORTION OF SYSTEM 2.

2-1. INSTRUMENTATION.

2-2. Circuit design of instrumentation to accomplish the primary navigation functions outlined in paragraph 5-0 of Progress Report No. 4 has been completed, and construction of the laboratory model equipment for field and flight tests is essentially complete. Production design of these units is underway and was completed for the first assemblies on 19 January 1956.

2-3. Circuit and mechanical design of instrumentation to accomplish two secondary navigation functions has been started. The first of these auxiliary devices will be used at the ground station as an aid in identifying the active mode of propagation. A cathode-ray tube, in conjunction with magnetic-drum storage, will be used to display the range pulses received from the aircraft.

2-4. The second auxiliary device is an automatic channel selector for the airborne equipment. The automatic channel selector will permit as many as four ground stations to interrogate the aircraft on the frequency channels determined by propagation predictions for each path. The rest frequency for the aircraft equipment will be that of the primary ground station and will be determined by the channel selector switch on the pilot's input device. After interrogation of the aircraft navigation equipment by the primary ground station, the airborne equipment will step to the frequency channel of the second ground-base station for interrogation. The equipment will then step to the frequencies of the third and fourth ground-base stations for further interrogation. After completion of this cycle, the equipment will rest on the frequency channel of the primary station until the next interrogation. The pilot may override the stepping cycle and return the equipment to the primary frequency channel in order to transmit a message.

2-5. The above method of automatic channel selection will require the secondary ground stations to interrogate on a schedule determined by the primary station. Since the frequency channel for each time of day for all ground stations except the primary will be set into the equipment before take-off, these stations must change frequency on a predetermined schedule.

2-6. COMPUTATION OF AIRCRAFT POSITION.

2-7. The geometry for a one-hop mode of propagation is shown *in figure 1*. The parameters involved in this figure are defined as follows:

$L = L_1 + L_2$ = radio path length from ground station to aircraft.

L_3 = path length from aircraft to ground which results from extending L_2 in a straight line.

h = virtual height of the ionosphere.

h_a = height of the aircraft.

R = radius of the earth.

r = true ground range of the aircraft with respect to the ground station.

$\phi_1 = \phi_2$ = the angle of incidence and reflection, respectively.

θ_1, θ_2, θ_3 have the definitions as given by figure 1.

L_1 and L_2 are not known separately, but the sum of $L_1 + L_2$ is known and is equal to one-half of the round-trip radio range from the ground station to the aircraft as measured by the equipment. The ground range, r, may be determined in terms of L, h and h_a if $\theta_1 + \theta_2$ is determined. The method used is to first solve for L_3, next solve for θ_3 and θ_1, and finally evaluate the quantity $2\theta_1 - \theta_3$ (which is equal to $\theta_1 + \theta_2$). The procedure is as follows:

a. From the assumption of $\phi_1 = \phi_2$,

$$L_1 = L_2 + L_3,$$

and by the law of sines, the relation

$$\left[\cos\theta_1 - \frac{R}{R+h}\right] L_3 (R+h) = \left[\cos\theta_3 - \frac{R}{R+h_a}\right] L_1(R+h_a) \qquad (1)$$

is derived. Substituting the exact relations

$$\cos\theta_1 = \frac{h^2 + 2R^2 + 2hR - L_1^2}{2R(R+h)} \qquad (2)$$

and

$$\cos\theta_3 = \frac{h_a^2 + 2R^2 + 2Rh_a - L_3^2}{2R(R+h_a)} \qquad (3)$$

into equation (1) results in

$$L_3^3 + 3L_3 \frac{(4A - 2B - L^2)}{3} - 2BL = 0 \qquad (4)$$

where $A = h^2 + 2hR$ and $B = h_a^2 + 2h_aR$.

There is only one real solution for equation (4)[1] for the condition that $q^3 + p^2 > 0$, namely: $L_3 = S_1 + S_2$ (5)

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[1] Ovid W. Eshbach, Handbook of Engineering Fundamentals (Second Edition: John Wiley and Sons, Inc., New York, 1952), p. 2-13.

where $S_1 = \left[p + (q^3 + p^2)^{1/2} \right]^{1/3}$

$S_2 = \left[p - (q^3 + p^2)^{1/2} \right]^{1/3}$

and

$p = BL$

$q = \dfrac{4A - 2B - L^2}{3}$

This condition is satisfied for all practical values of L, h, and h_a.

b. Once a value for L_3 is obtained, θ_1 and θ_3 are obtained from

$$\cos \theta_1 = 1 - \frac{(L + L_3)^2 - 4h^2}{8R(R + h)} \qquad (6)$$

and

$$\cos \theta_3 = 1 - \frac{(2L_3)^2 - 4h_a^2}{8R(R + h_a)} \qquad (7)$$

c. From equation (6) and (7)

$$r = (2\theta_1 - \theta_3)R$$

$$= 2R\cos^{-1}\left[1 - \frac{(L + L_3)^2 - 4h^2}{8R(R + h)}\right] - R\cos^{-1}\left[1 - \frac{(2L_3)^2 - 4h_a^2}{8R(R + h_a)}\right] \qquad (8)$$

which gives the ground range in terms of L, h, and h_a for a one-hop mode.

2-8. The solution for the two-hop mode can be obtained by use of the method and results for the one-hop mode. The geometry for the two-hop mode is illustrated in figure 2 where

L = $3L_4 + L_5$ = the one-way radio path length.

$2L_4$ = the one-way radio path length for the first hop.

$L_4 + L_5$ = the one-way radio path length for the second hop.

h = height of reflection.

h_a = height of aircraft.

R = earth's radius.

$\theta_4 = \theta_5 + \theta_6$ = angles indicated in figure 2.

r = ground range from ground station to aircraft.

It is assumed that the heights of reflection for the two hops are equal and that L, h, and h_a are known. The ground range, r, can be determined if any two of the quantities θ_4, θ_5 and θ_6 are determined or if L_6 is determined. The procedure for determining L_6 is to utilize the results for the one-hop mode. The second hop of the two-hop mode is identical to the one-hop mode where $L_4 = L_1$, $L_5 = L_2$ and $L_6 = L_3$. If $L_4 + L_5$ were known, L_6 could be determined as in paragraph 2-7. Unfortunately, $L_4 + L_5$ cannot be determined directly. However, since by symmetry $L_4 = L_5 + L_6$,

$$L = 3L_4 + L_5 = 2(L_4 + L_5) + L_6$$

or $\frac{L}{2} = L_4 + L_5 + \frac{L_6}{2}$ can be expressed in terms of the one-hop mode

as $\frac{L}{2} = L_1 + L_2 + \frac{L_3}{2}$

2-9. The solution for the two-hop mode is obtained by constructing a curve of $L_1 + L_2 + \frac{L_3}{2}$ against L_3 for each value of h and h_a from the one-hop mode calculations. This curve is used to determine L_6 (which is equal to L_3) by entering this curve with the value for $\frac{L}{2}$. The ground range, r, for the two-hop mode is then given by

$$r = 4R\cos^{-1}\left[1 - \frac{\left(\frac{L + L_6}{2}\right)^2 - 4h^2}{8R(R + h)}\right] - R\cos^{-1}\left[1 - \frac{4L_6^2 - 4h_a^2}{8R(R + h_a)}\right] \qquad (9)$$

2-10. Equations 8 and 9, which describe r as a function of L, h, and h_a, can be represented conveniently for graphical determination of r by plotting L - r against r. The curves are drawn for values of h representing different E and F_2 layer heights and one- and two-hop modes, for a fixed value of h_a. Figure 3 illustrates the nature of this presentation. This figure shows L - r versus r for the one-hop modes only, and has been computed for an aircraft altitude of zero. Curves furnished for operational use will include the two-hop E and F modes, and will be computed for operational altitude.

2-11. In figure 3, a line of constant L, for some given value of L, has as its X intercept a value of r = L and has a negative slope equal to the ratio of the L - r axis scale to the r axis scale (five, in the case of figure 3). This line of constant L intersects the lines representing values of constant h for the various modes. These intersections are the solutions to equations 8 and 9 for a given value of L, giving the values of r for various values of h. If r is accurately known by some independent means (such as a visual fix), the layer height and active mode of propagation are uniquely determined. If the layer heights are known, the active mode may be identified from an approximate value of r obtained from the estimated aircraft position, and thus r can be uniquely determined. The following example will illustrate these statements.

a. On figure 3 the line, AB, is a line of constant L with a value of 1000 nautical miles.

b. Lines CD and EF are lines of constant r.

c. In this example, one-half the total round-trip radio path length is equal to 1000 nautical miles, and from a visual fix it has been found that r equals 985 nautical miles (point C).

d. The intersection at point D determines that the active mode of propagation is one-hop E with a vertical layer height of 110 km.

e. If the assumption that r is equal to 985 nautical miles is based only upon an approximate knowledge of the aircraft position, then the position of point D can only be used to indicate that one-hop E is the active mode, and a knowledge of the E-layer vertical height is required to determine the ground range accurately.

2-12. As another example, (given the same radio-path length, L):

a. Where a visual fix gives a value of r represented by point E, the propagation mode is one-hop F_2 with a vertical height of 320 km.

b. If the value of r is found by dead reckoning, then intersection F indicates a one-hop F_2 mode, and a knowledge of the F_2 vertical height is required to determine the ground range accurately.

2-13. The use of separate locations for the transmitting and receiving ground stations increases the possibility of having two different modes of propagation for the forward and return trip in cases where two modes of propagation are active and of nearly equal strength. Assume that this is the case and that the aircraft range is known to be equal to that indicated by point G. The intersection at point H, of the line corresponding to r = G and the line representing constant L, indicates a one-hop F_2 mode of propagation with a vertical height of approximately 235 km. However, if it has been established that the height of the F_2 layer is 320 km and the height of the E layer is 110 km, it is apparent that point H does not represent the true modes of propagation. In practice, r will be determined as follows:

a. The line representing constant L will be established.

b. The range will be determined on the basis of the F_2 mode of propagation, but this range will be rejected on the basis of the approximate position of the aircraft.

c. The range will next be determined on the basis of the E mode of propagation, but this range will also be rejected on the basis of the approximate position of the aircraft.

d. Finally, the point along the constant-L line which exactly bisects the vertical line segment between the two known h curves will be established (point H). This point determines the true ground range (point G).

2-14. The geographic coordinates of the aircraft are determined by the ground ranges of the aircraft in relationship to two ground stations. The method used for translating the two ground ranges into geographic coordinates, such as latitude and longitude, can either be of an analytic or of a graphic form. In either case, two solutions are given which are symmetrically placed with respect to the great circle connecting the two ground stations. One of these solutions may be eliminated by inspection. The graphic method is the most convenient means of converting range data to position data. The aircraft's position is fixed by the intersection of two circles whose centers are midway between the transmitting and receiving antennas of each ground station and whose radii are the ground ranges. A Lambert conformal conic projection with a scale of 1:3 million or 1:2 million is an excellent chart for this purpose. For optimum accuracy, the change of scale with latitude should be taken into account. Using the U.S. Coast and Geodetic Survey Chart No. 3060C with a scale of 1:3 million, distances were measured between cities using the scales provided on the chart, and the distances were compared with known values.[1] This exercise indicated that chart measurements could be made to an accuracy of one and one-half nautical miles over distances of 2600 miles.

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[1] C. A. Whitten, *Air-Line Distances Between Cities in the United States* (U.S. Dept. of Commerce Special Publication No. 238).

3-0. COMMUNICATION PORTION OF SYSTEM 2.

3-1. Circuit designs of the airborne-transmitter power amplifier and high-voltage power supply and of the antenna network were completed on 6 January 1956. These units are presently in the production design phase. Release of this design is scheduled for 15 February 1956. Construction of models for flight test is also scheduled for completion by 15 February 1956.

3-2. Redesign of some portions of the airborne and ground-based exciter circuits has been found to be desirable. This necessitates new layouts in slightly larger packages. Completion of these designs is scheduled for 15 February. Models for the flight test are being constructed concurrently with the package design. The airborne exciter model will be completed for the flight tests by 15 February 1956. During tests the ground station will use the previous design as an interim measure, pending completion of the newly designed equipment.

4-0. TOTAL MAN-HOURS EXPENDED. A total of [redacted] man-hours has been expended on System No. 2 (navigation portion and communication portion) during the period covered by this progress report.

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COPY 2 OF 5